

# Achievable Science with SmallSats/CubeSats

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Remote Sensing Seminar Series  
University of Colorado at Boulder

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## JPL is part of NASA and Caltech



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- 6,200 Employees
- 167 Acres (includes 12 acres leased for parking)
- 139 Buildings; 36 Trailers
- 673,000 Net Square Feet of Office Space
- 906,000 Net Square Feet of Non-Office Space (e.g., Labs)

# 2017 Anniversaries

## 5 Years

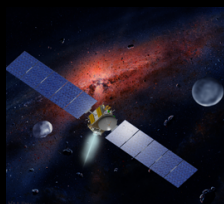


NuSTAR



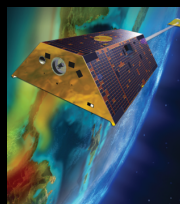
Curiosity

## 10 Years



DAWN

## 15 Years



GRACE

## 20 Years



Mars Pathfinder



Cassini

## 25 Years



Topex/Poseidon

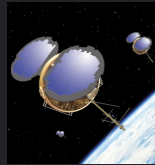
## 40 Years



Voyager

## Present and Near Future, Smallsats Creeping in ...

2018



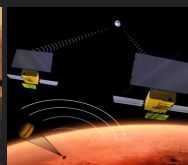
COSMIC-2



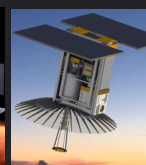
GRACE-FO



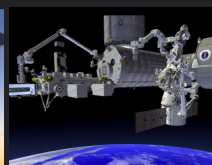
InSIGHT



MarCo



RainCube



ECOSTRESS

2020



Mars 2020

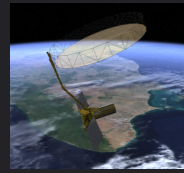


Mars Helicopter

2021

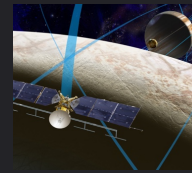


SWOT



NISAR

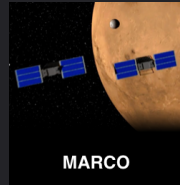
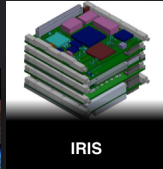
2022



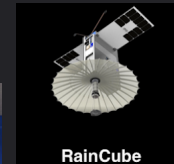
Europa Clipper



PSYCHE



And now covering the alphabet



# Decadal Surveys

- Reports prepared by National Academy of Sciences at the request of Congress and NASA
- 10-year plans outlining scientific goals and missions representing input from scientists leaders in the field in Astrophysics, Planetary Science and Earth Science communities in the United States (and beyond)
- Represents the official consensus on the top priority scientific goals, and the missions required to satisfy them

# *How can we best use assets to afford certain types of missions at lower cost?*

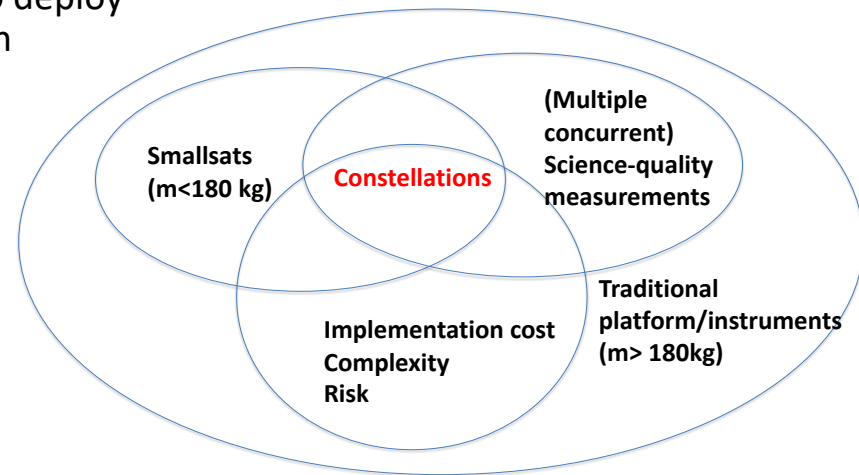
- In the cost-constrained environment of NASA, the need for an acceptable compromise between science objectives and mission affordability is informing the decadal surveys
- Can we accomplish, e.g., 70% of the measurements for, e.g., 50% of the “regular” cost?
- What types of measurements lend themselves to that type of compromise?

# Motivation

- The rising credibility of CubeSats as science platforms has changed significantly in the last few years
- While cost is a big factor, access to space and the ability to deploy multiple spacecraft has inspired people to develop mission concepts that exploit the new capability
- SmallSats/CubeSats show capability of science quality\* measurements enabled by:
  - Significant instrument miniaturization advances
  - Advances in small spacecraft buses
  - Flexibility in launch and deployment approaches
  - Creativity in mission architecture design
  - End-to-End affordability
- Focus on Science: New scientific observations are possible, via constellations, formation flying, and sensor disaggregation

Cubesat = 4 to 25 kg (3U to 12U)

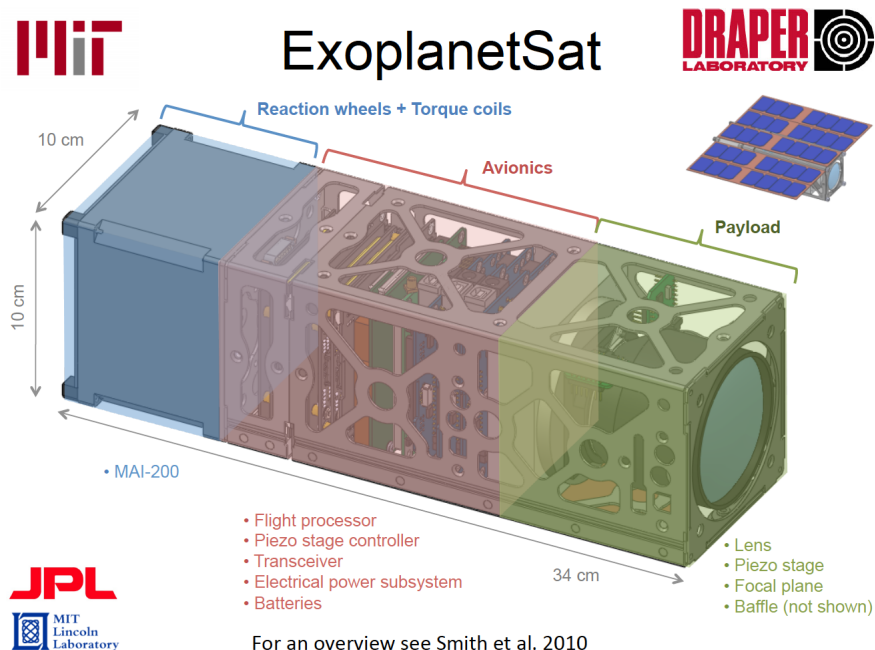
ESPA-compatible smallSat = 25 to 180 kg



This talk discusses the value added to planetary science, heliophysics, earth science, and astrophysics **measurements** by single smallsats and constellations

\*Equivalent to that of traditional instrument/platform or degraded but still acceptable

# Miniaturization



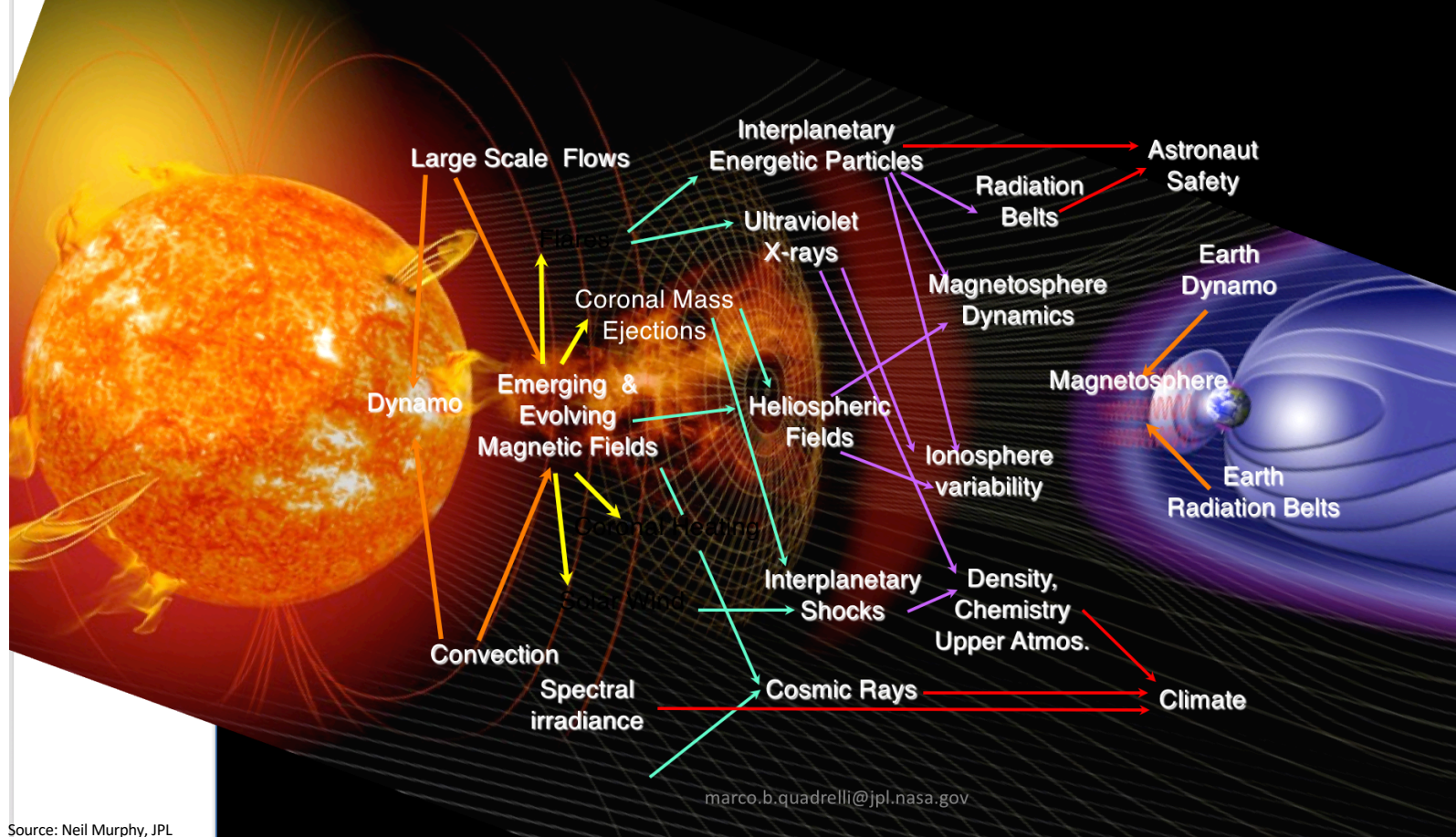
For an overview see Smith et al. 2010

Source: Sara Seager, MIT

# Systems of Distributed CubeSat/SmallSats are Game-changers

- New scientific observations are possible, **specifically exploiting the concepts of constellation or formation**
- Advantages of constellations:
  - Topologies: Possibility of distributed and heterogeneous measurements
    - Sensor heterogeneity → Multiple types of spectrometers, Spectrometer + imager, Organics in-situ sampler + fields
    - Heterogeneous constellations → Different revisit times on different orbits, Large data volumes, DSN/TDRSS/GPS involved
    - Lower altitude (stratospheric, suborbital) + higher (LEO, GEO) → would enable a sensor web across multiple domains
  - Density: Possibility of increased density and spatio-temporal resolution with constellations (e.g.: CYGNSS)
    - Higher temporal resolution and spatial sampling → require critical orbit coverage
    - Increased robustness → leads to graceful degradation with large numbers of low-cost detectors
  - Precision: Possibility of more precise timing/ranging with formations
    - Achieving high ground resolution → requires tight relative pointing & control
    - Enabling high levels of instrument synthesis → requires multiple baseline interferometry
    - Leveraging precise clock, ranging → leads to costly sensor calibrations
    - Availability of increased autonomy → enables agile retargeting, repointing, reconfiguration
  - Leverages increasing availability of small instruments

# A Complex, Coupled System



Source: Neil Murphy, JPL

# Science Case for Heliophysics

Measurement(s)	SmallSat candidate?
Boundary and solar wind plasma measurements Energetic neutral atoms Direct samples of interstellar matter and solar wind, magnetic field, suprathermal ions	Yes
Wind velocity and temperature between 80 and 300 km Far UV imager for species altitude profiles and distributions Ion and neutral wind velocity and mass spectrography	Yes
Image plasmasheet and ring current energetic neutral atoms Evolution of plasma density via EUV imaging. Near Earth FUV emissions In situ ion and electron plasma densities, temperatures, velocities to 30 keV, and in-situ magnetic fields.	Yes
Use 6 identical Satellites occupying 30 deg separated orbital planes in 450 km circular orbits Measure neutral and ion velocities, temperature, densities, composition, vector magnetic fields, electron distribution between 0.05 eV and 20 keV	Yes
Tomographic images of plasma density in magnetotail, flank, and subsolar magnetosphere 3-axis flux magnetometer Electrostatic analyzers Radio tomography instrument	Yes
3-axis magnetic fields 3D ion-electron plasma analyzer Energetic ion-electron particle telescope	Yes

- Capturing **coupled** phenomena in heliophysics require multi-point (and often multi-orbit) in-situ and remote-sensing measurements in key regions in the Sun-Earth domain, which naturally lead to large constellations

Science Area	Smallsat-enabled mission concept for LWS program
Solar outputs	<ul style="list-style-type: none"> <li>• Stereoscopic EUV imaging</li> <li>• Magnetography well off the Sun-Earth line</li> </ul>
Ionospheric inputs	<ul style="list-style-type: none"> <li>• A solar wind constellation that observes from ~ 30 RE upstream</li> <li>• An ionospheric constellation to drive coupled magnetospheric-ionospheric models</li> </ul>
Satellite drag and thermospheric density	<ul style="list-style-type: none"> <li>• Fleet of 12U–27U 3-axis stabilized smallsats</li> </ul>
Plasmaspheric plasma irregularities	<ul style="list-style-type: none"> <li>• Active direct measurement (VHF-UHF Radio) of TEC</li> <li>• Passive indirect measurements (UV) of TEC</li> </ul>
TEC and scintillation	<ul style="list-style-type: none"> <li>• Active direct measurement (VHF-UHF Radio) of TEC</li> <li>• Passive indirect measurements (UV) of TEC</li> </ul>
Solar energetic particles	<ul style="list-style-type: none"> <li>• Low-frequency Imaging Array in Space</li> </ul>

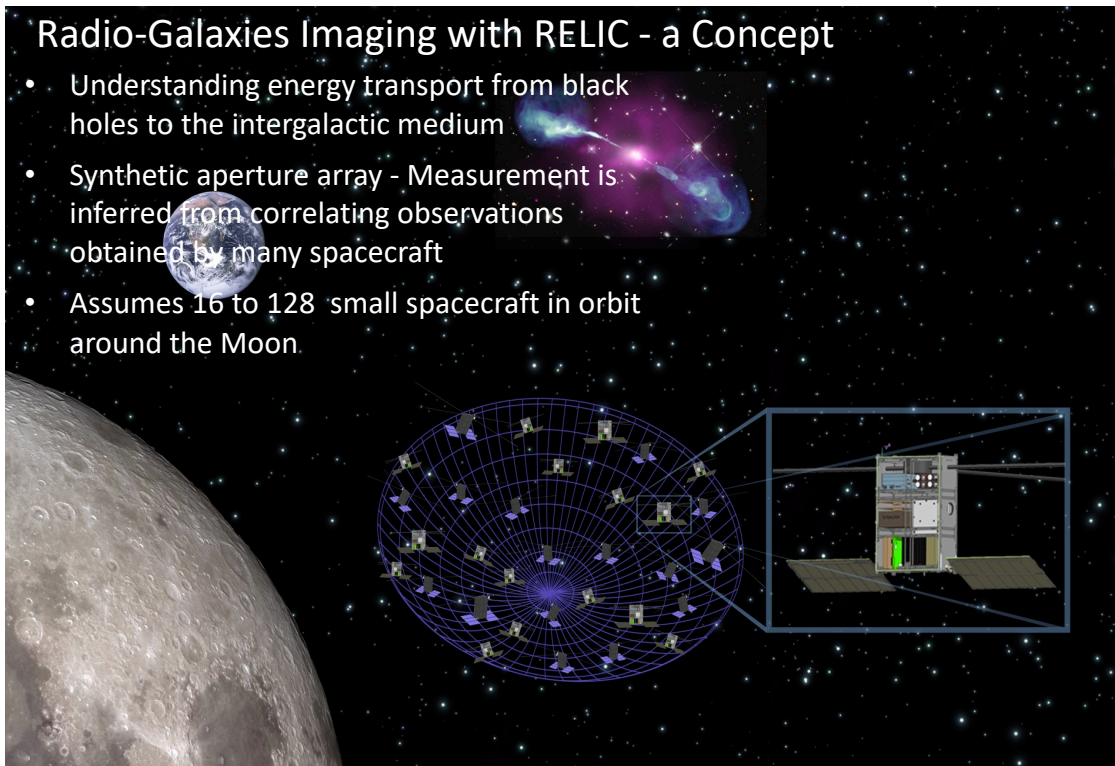
Source: Neil Murphy, JPL

LWS = Living With a Star

# Examples of SmallSat and Constellation for Astrophysics

## Radio-Galaxies Imaging with RELIC - a Concept

- Understanding energy transport from black holes to the intergalactic medium
- Synthetic aperture array - Measurement is inferred from correlating observations obtained by many spacecraft
- Assumes 16 to 128 small spacecraft in orbit around the Moon.



ASTERIA (Arcsecond Space Telescope Enabling Research in Astrophysics) is a technology demonstration and opportunistic science mission to conduct astrophysical measurements using a CubeSat.

Launched in 2017, it achieved 0.5 arcsecond-level line of sight pointing error and highly stable ( $<0.01\text{K}$ ) focal plane temperature control. Relevant for precision photometry, i.e., the measurement of stellar brightness over time. Precision photometry, in turn, provides a way to study stellar activity, transiting exoplanets, and other astrophysical phenomena.

# Science Case for Astrophysics

Opportunities for smallSats are limited:

- Discipline dominated by need for photons and small resolution, typically requiring large apertures
- Small instruments typically cannot yet exceed the capabilities of ground-based instruments
- Sophisticated detectors generally not amenable to miniaturization
- Challenging yet to do high-energy astrophysics (gamma ray), as large masses are required to stop high energy photons.

- There are niches for which smallSats could be valuable:
  - Radio interferometers
  - Stellar variability (including monitoring stars for transits)
  - Time Domain Astronomy with UV for high energy transient events
- There are demonstrated examples of smallSats in Astrophysics:
  - The MOST<sup>1</sup> mission had a steady publication record, and the BRIT<sup>2</sup> constellation is flying now.
  - ASTERIA<sup>3</sup>, SPARCS<sup>4</sup>: both missions are examples that could easily be extended to be constellations and/or swarms.

Source: Astrophysics Roadmap

<sup>1</sup>Microvariability and Oscillation of Stars

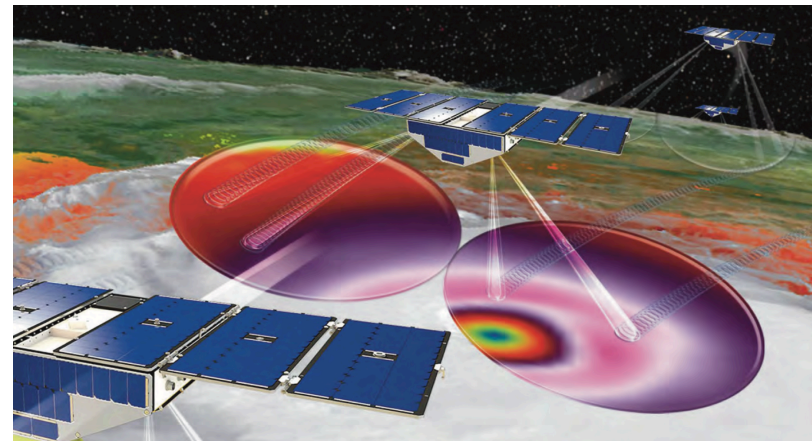
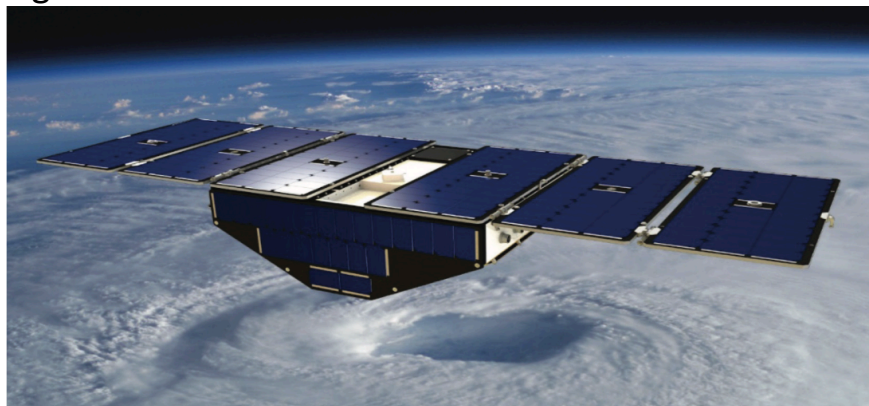
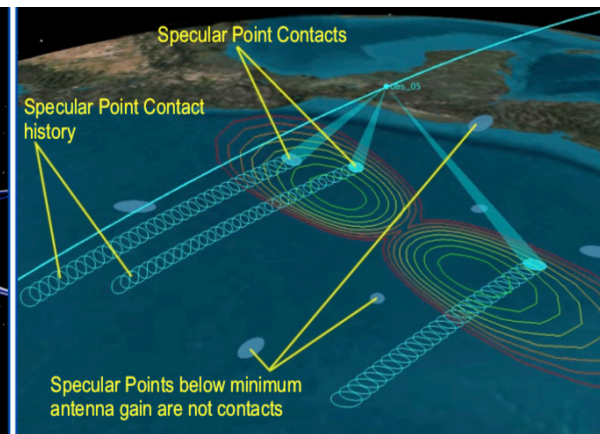
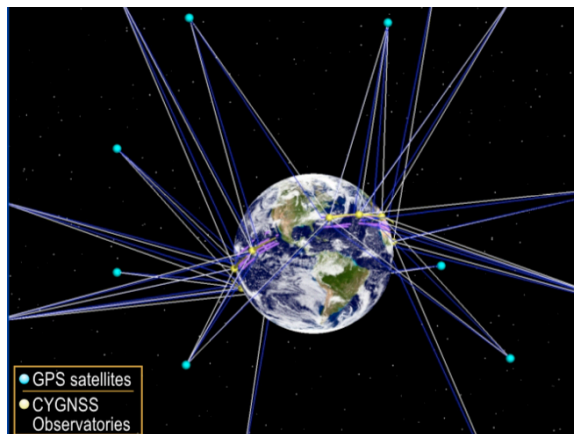
<sup>2</sup>BRIT Target Explorer

<sup>3</sup>Arcsecond Space Telescope Enabling Research in Astrophysics

<sup>4</sup>Star-Planet Activity Research Cubesat

# CYGNSS as an Example of SmallSat Constellation for Earth Science

- Univ. of Michigan led
- Example of sensor disaggregation: GPS transmitter and reflection receiver form a bi-static radar pair
- Non-traditional sampling of wind fields to yield sea-surface wind speeds
- New data product characteristics due to novel observation geometries



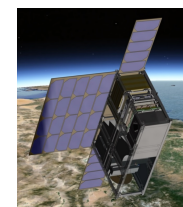
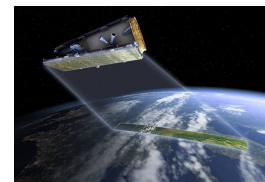
# Science Cases for Earth Science – ESAS-2017 Designated and Explorer

Target Observable	Candidate Measurement Approach	SmallSat Potential
<b>Aerosols</b>	Backscatter Lidar and Multichannel/Multiangle polarization imaging radiometer (same platform)	Yes: ESPA-Class on same platform or constellation on separate platforms. Lidar technology needed.
<b>Clouds, Convection, &amp; Precipitation</b>	Radar(s) with multi-frequency passive microwave and sub-mm radiometer	Yes: ESPA/CubeSat constellations. Deployable aperture antenna technology needed.
<b>Mass Change</b>	Spacecraft ranging measurement of gravity anomaly	Near-Term: ESPA-Class constellations. Laser-ranging, targeting, spacecraft stability needed.
<b>Surface Biology &amp; Geology</b>	Hyperspectral imagery (visible, SWIR), Multi/Hyperspectral imagery in the thermal IR	Yes: ESPA-Class constellations on same or multiple platforms.
<b>Surface Deformation &amp; Change</b>	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	Yes: ESPA-Class constellations. On-board processing, large deployable apertures, formation flying needed.
<b>Greenhouse Gases</b>	Multispectral short wave IR and thermal IR sounders or Lidar	Yes: ESPA-Class or MiniSat constellation for SWIR and Thermal IR. Lidar technology needed.
<b>Ice Elevation</b>	Lidar	Long-Term: Lidar technology needed.
<b>Ocean Surface Winds and Currents</b>	Radar scatterometer	Near-Term: ESPA-Class or MiniSat constellation.
<b>Ozone and Trace Gases</b>	UV/IR/microwave limb/Nadar sounding and UV/IR solar/stellar occultation	Near-Term: ESPA-Class to CubeSat constellations. Spectrometer development needed.
<b>Snow Depth and Snow Water Equivalent</b>	Radar (Ka/Ku band) altimeter or Lidar	Near-Term (as a spectrometer). Long-Term as Ka/Ku Radar or Lidar in ESPA-Class constellation.
<b>Terrestrial Ecosystem Structure</b>	Lidar	Long-Term: Lidar technology needed.

## Surface Deformation & Change

**NovaSAR-S Small Satellite Synthetic Aperture Radar Platform**

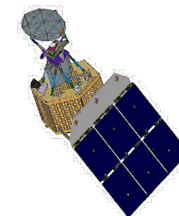
Surrey Satellite Technology SSTL



## Snow Depth & Snow Water Equivalent

**Snow and Water Imaging Spectrometer (SWIS)**  
Jet Propulsion Laboratory

**Aerosols Hyperangular Rainbow Polarimeter (HARP)**  
Univ. of Maryland Baltimore County

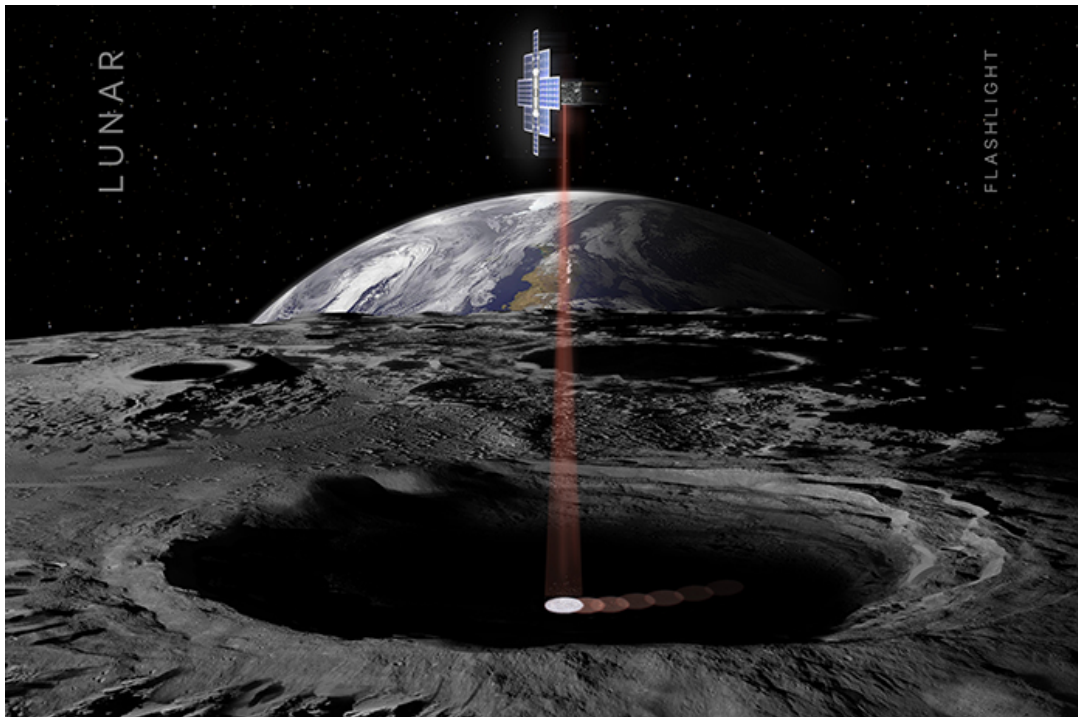


## Ocean Surface Winds & Currents

**Compact Ocean Wind Vector Radiometer (COWVR)**  
USAF/ORS and Jet Propulsion Laboratory

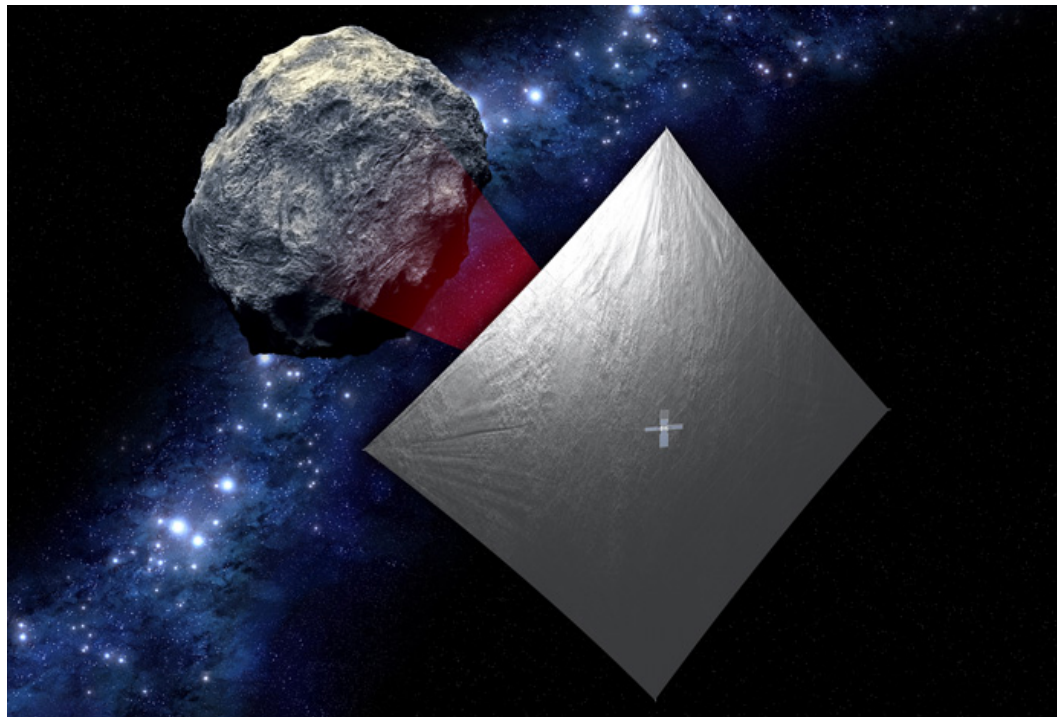
# Example 1 of Cubesat for Planetary Science

- Lunar Flashlight locates ice deposits in the Moon's permanently shadowed craters to detect composition, quantity, distribution, form of water/H species and other volatiles associated with lunar cold traps
- Uses its near infrared lasers to shine light into the shaded polar regions, while the on-board spectrometer measures surface reflection and composition
- Heritage from predecessor JPL cubesats such as INSIGHT and MARCO, and Moon Mineralogy Instrument
- Launch: November 2018
- Secondary payload on SLS for Orion test



# Example 2 of Cubesat for Planetary Science

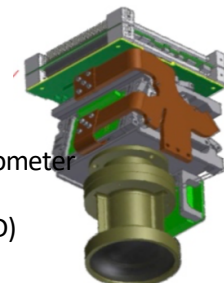
- NEA Scout, will travel to a near-Earth asteroid using a CubeSat and solar sail propulsion
- Will flyby and observe a small asteroid (<300 feet in diameter) with a science grade multi spectral camera, taking pictures and observing its position in space, the asteroid's shape, rotational properties, spectral class, local dust and debris field, regional morphology and regolith properties
- Launch: November 2018
- Secondary payload on SLS for Orion test



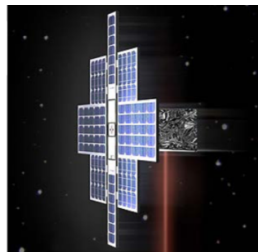
# Science Case for Planetary Science

Science themes	Measurement categories	Potential for distributed measurements using constellations
Building New Worlds	Tunable laser Spectrometer (TLS)	Multi probes in Venus, Mars and giant planet atmosphere
Building New Worlds	Quadrupole Ion Trap spectrometer (QITMS)	Multi probes in Venus, Mars, and giant planet atmosphere
Building New Worlds	Magnetometers	Additional mag sensors on Psyche, missions to the Moon
Planetary Habitats	Thermal IR imager, Bolometer (SoA, 10-100 micron), Thermopile array (10-26 micron)	Combination of detectors at multiple vantage points (orbiter + landers)
Planetary Habitats	Quadrupole Ion Trap spectrometer (QITMS)	Not evident science driver for targets of interest (Europa/Enceladus plumes)
Planetary Habitats	Magnetometers Energetic particle spectrometer	Distributed sensors at icy moons (especially Europa)
Solar System Workings	Thermal IR imager, Bolometer (SoA, 10-100 micron), Thermopile array (10-26 micron)	Combination of detectors at multiple vantage points (orbiter + landers)
Solar System Workings	Magnetometers Energetic particle spectrometer	Distributed sensors for giant planets, Europa, Venus

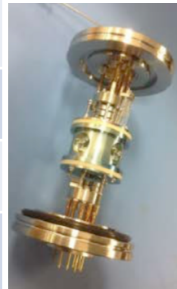
HARP Imaging Polarimeter (3U)  
UMBC/SDL (2017)



Lunar Flashlight NIR Laser (6U) MSFC/JPL (2017)



Mass Spectrometer (3U)  
JPL (TBD)



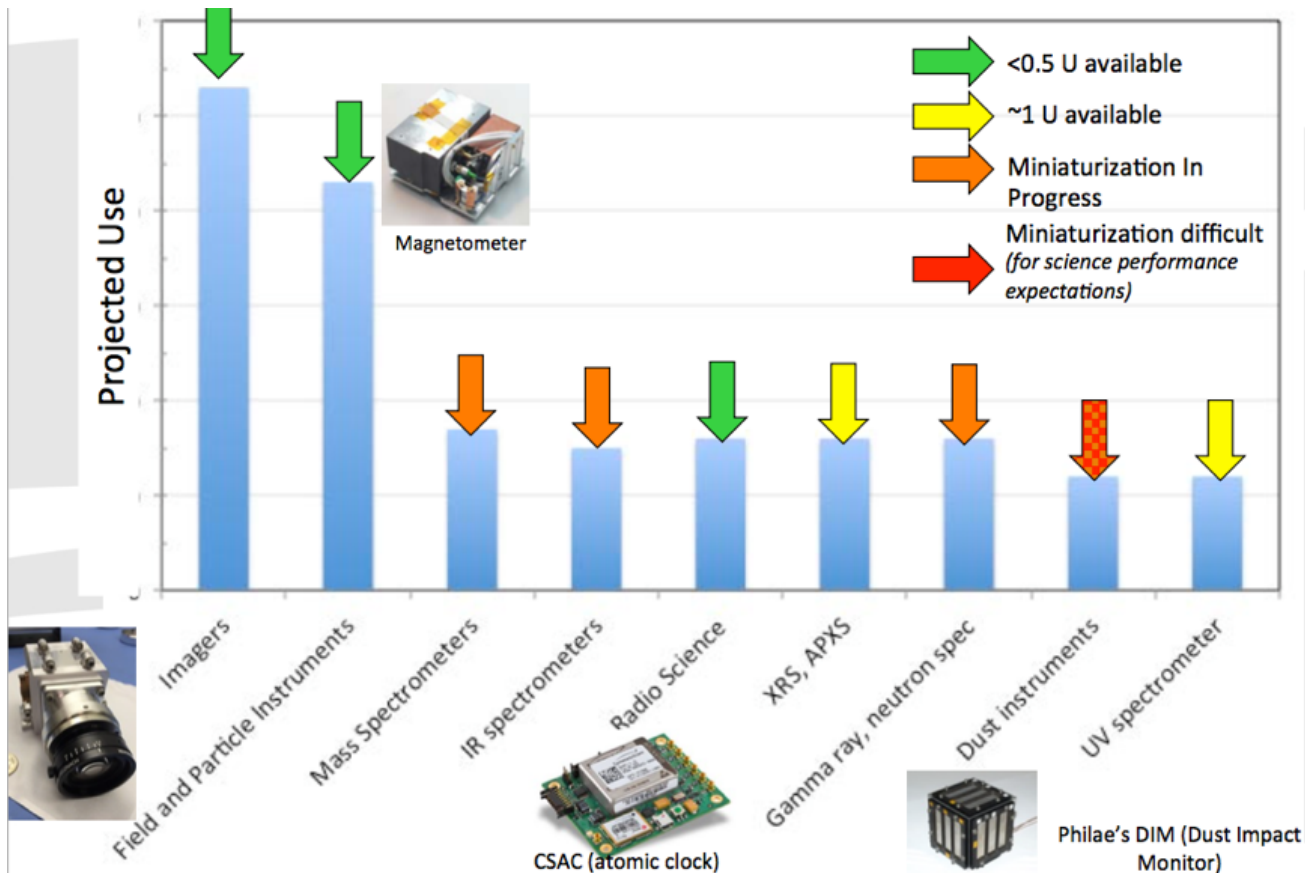
LunarIceCube IR Spectrometer (6U)  
GSFC (2018)



*Disclaimer: The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.*

- In planetary science, the big contribution of CubeSats/smallSats is to provide access to targets that are not necessarily high on NASA's priority list.
- Many targets can be explored within the constraints of the SIMPLEX program (\$55M, secondaries on Discovery launches).
- Specific topics that are of interest to the community but don't necessarily have a place in the decadal survey can also be approached with CubeSats/smallSats, e.g., NEO reconnaissance for in situ resource assessment.

# Planetary Science Instruments on cubesats



# Innovative Science with SmallSats constellations

Domain	Instruments/measurement types/architectures
<b>Planetary Science</b>	<ul style="list-style-type: none"> <li>Multiple TLS/QITMS/thermal imaging spectrometers would collect and analyze elements and provide thermal data at separate spatial locations and different times if on different orbits.</li> <li>Constellations will be useful to sample magnetic and plasma field at multiple locations. Would need &gt;10 CubeSats. Sampling of many bodies within a population.</li> <li>CubeSats distributed across the rings of Saturn.</li> <li>SmallSats sampling multiple comets as part of the same mission</li> </ul>
<b>Heliophysics</b>	<ul style="list-style-type: none"> <li>Stereoscopic EUV imaging.</li> <li>Magnetography well off the Sun-Earth line.</li> <li>A solar wind constellation that observes from ~ 30 RE upstream.</li> <li>An ionospheric constellation to drive coupled magnetospheric-ionospheric models.</li> <li>Fleet of 12U–27U 3-axis stabilized smallSats.</li> <li>Active direct measurement (VHF-UHF Radio) of TEC.</li> <li>Passive indirect measurements (UV) of TEC.</li> <li>Low-frequency Imaging Array in Space</li> </ul>
<b>Earth Science</b>	<ul style="list-style-type: none"> <li>Backscatter Lidar and Multichannel/Multiangle polarization imaging radiometer (same platform)</li> <li>Radar(s) with multi-frequency passive microwave and sub-mm radiometer</li> <li>Spacecraft ranging measurement of gravity anomaly</li> <li>Hyperspectral imagery (visible, SWIR), Multi/Hyperspectral imagery in the thermal IR</li> <li>Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction</li> <li>Multispectral short wave IR and thermal IR sounders</li> <li>Radar scatterometer</li> <li>UV/IR/microwave limb/Nadar sounding and UV/IR solar/stellar occultation</li> <li>Radar (Ka/Ku band) altimeter</li> <li>Radio-occultations</li> </ul>
<b>Astrophysics</b>	<ul style="list-style-type: none"> <li>Synthetic aperture arrays for radio astronomy, radio interferometers, imagers for stellar variability (including monitoring stars for transits), Time Domain Astronomy with UV for high energy transient events</li> <li>Self-assembled segmented telescopes in visible/IR/UV</li> </ul>

# Summary

Domain	Science with smallsats	Constellations	Formations
<b>Planetary Science</b>	Established	- Many possibilities - 100's of asteroid mappers	-Not yet
<b>Heliophysics</b>	Established	- Many possibilities offered by need to explore coupled phenomena	-Radio Interferometry (SunRISE)
<b>Earth Science</b>	Established	- There are already proposed / selected active missions that utilize small/cubeSats - Constellations of 100's cubeSats for radio occultation and imaging launched by emerging space companies	- Several proposed: D-TRAIN, SABLE, TEMPEST EV, smallSat GRACE, 3D Winds from passive approach
<b>Astrophysics</b>	Emerging	- Radioastronomy (Optical/Radio-interferometry)	- Radio-galaxy imaging (RELIC)

- CubeSat/SmallSats and constellations are game-changers in terms of making certain measurements possible
- Future work: Quantification of science return vs. implementation and operation cost, risk, and complexity is being assessed via ongoing decadal-class science concepts and new ideas for the next Planetary Science, Heliophysics, Earth Science, and Astrophysics Decadal Surveys.

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